Chapter 4
Sewer Sediment Solids

Introduction

Deposition of sewage solids during dry weather in combined sewer systems has long been recognized as a major contributor to "first-flush' phenomena occurring during wet-weather runoff periods. Estimation of these loadings for a given sewer system is an extremely difficult task. Measurement for extended periods is possible but extremely expensive. Techniques presently available to estimate dry weather deposition in sewerage systems involve the use of computer models that are both complex and expensive and requiring more effort than appropriate for preliminary "first-cut" assessments (Sonnen, 1977; Ashley et al., 1999; Bachoc, 1992).

The U.S. Environmental Protection Agency developed a set of generalized procedures for estimating pollutant loadings associated with dry weather sewage solids deposition in combined sewer systems. It utilizes data and information from three sewerage systems in eastern Massachusetts (Pisano and Queiroz, 1977) and one in the City of Cleveland, Ohio (Pisano and Queiroz, 1984). A complete exposition of the analysis procedure, assumptions and methodologies has been previously given in two aforementioned referenced documents, and will not be presented here.

The predictive equations developed in the previous study relate the total daily rates of pollutant deposition within a collection system to physical characteristics of collection systems such as per capita waste rate, service area, total pipe length, average pipe slope, average diameter and other parameters that derive from analysis of pipe slope characteristics. Several alternative predictive models were presented reflecting anticipated differences in the availability of data and user resources. Pollutant parameters include suspended solids (SS), volatile suspended solids (VSS), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), organic nitrogen by the Kjeldahl method (TKN) and total phosphate (TP). Sewer system age and degree of maintenance were also considered. Factors were presented for estimating the increase in collection system deposition resulting from improper maintenance. The empirical least squares approach was used to formulate the final equations that are presented along with summarized results from the previous study.

Overview of Approach

An empirical model relating pollutant deposition loading to collection system characteristics is described in this Chapter. The approach is to use least squares to fit parameters of a postulated model. The model form is a single-term power function relating total daily sewage solids deposition over a collection system to simple sewer catchment characteristics, including service area, length of pipe and average pipe slope. The major steps in the analysis are depicted in Figure 1. Sewer system data including manhole-to-manhole length, slope, size, shape and age are assembled for entire collection systems in Step A. This information is used in Step B to compare total daily sewage solids deposited in these collection systems for a wide variety of different operating conditions. These quantities are estimated using an existing exogenous model that uses extremely detailed information to compute deposition loadings throughout an entire collection system network.

The simulated deposition loadings for different input conditions constitute the dependent variable data in the regression analysis. The independent variable data is prepared in Step C as a result of the analysis of assembled data from Step A and detailed outputs from Step B. The dependent variable data was generated from an exogenous predictive analysis, while the independent variable data was obtained from primary collection system data and from a secondary analysis of the exogenous simulation outputs with selected collection system data.

The regression analysis is performed in Step D to prepare the simplified predictive relationships. The entire process is designed to eliminate using the complicated network model requiring thousands of individual bits of technical information.

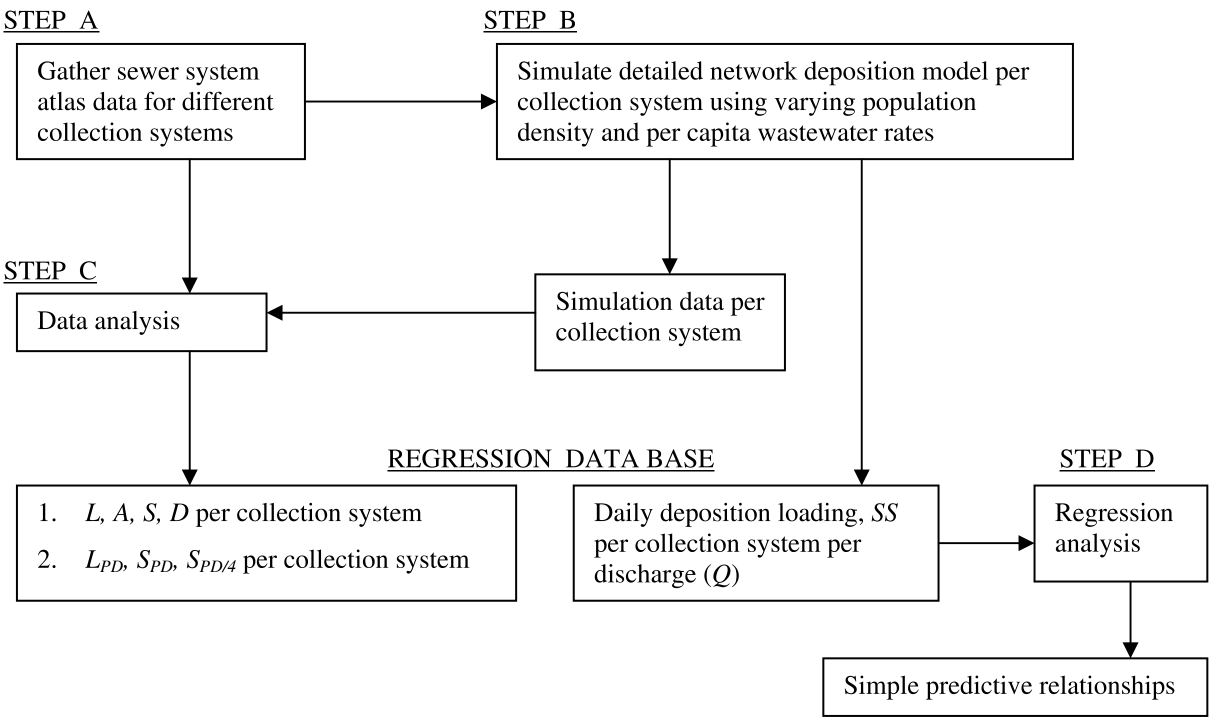

Figure 1. Overview of Method of Approach

Independent and Dependent Variables

The list of variables considered in the regression analysis is the following:

1. Total collection system pipe length (L) -- ft or m
2. Service area of collection system (A) -- acre or ha
3. Average collection system pipe slope (S) -- ft/ft or m/m
4. Average collection system pipe diameter (D) -- in. or mm
5. Length of pipe corresponding to 80% of the solids deposited in the system (L_{PD}) – ft or m
6. Slope corresponding to L_{PD} (S_{PD}) -- ft/ft or m/m

7. Slope corresponding to 1/4 of the percentage of pipe length (L_{PD}) below which 80% of the solids deposit ($S_{PD/4}$) -- ft/ft or m/m
8. Flow rate per capita, including allowance for infiltration (Q) -- gpcd or Lpcd
9. Daily total sewage solids deposition loading in collection system (TS) -- lb/d or kg/d (dependent variable predicted from deposition model)

It was determined in the prior study that the mean pipe slope alone would not be adequate to explain the effects of the pipe slopes on the variations of the deposition loads. A better characterization of the sewer slopes could be obtained by defining various parameters at the flatter sewer slope range. Two other pipe slope parameters besides the mean pipe slope were selected for inclusion into the regression model.

The collection system slope parameters S_{PD} and $S_{PD/4}$ were arbitrarily defined with the sole aim of better defining the range of the pipe slope distribution function. These collection system slope parameters were defined after reviewing several plots of the cumulative distribution of pipe slopes for several collection systems. Other choices could have also been made.

Estimates of collection system pipe length, service area, average pipe slope and average diameter were prepared from direct inventory and analysis of sewer system atlas information. Estimates of L_{PD}, S_{PD} and $S_{PD/4}$ were prepared from a detailed analysis of simulated data generated from a complex sewer system network deposition model. The total daily deposition load, *TS*, is also computed using this model. Finally, it is clear that the deposition process is also strongly affected by the wastewater flows in the system. Variations in population density and the degree of infiltration affects the dry weather flow rates. These effects were incorporated into the per capita wastewater rates (Q) used in the deposition model simulations and in the regression analysis.

Models

Both linear additive and multiplicative models were investigated. Untransformed observed values of the dependent and independent variables are initially used, leading to a strictly linear regression equation. In another case the observed values of both the dependent and independent variables were transformed by taking their natural logarithms, leading to a linear equation in the logarithmic domain which can be put into a non-linear multiplicative form.

Regression Method

The linear regression program used to empirically establish the relationships of the total daily suspended solids (*TS*) deposition within a sewerage collection system with the independent variables is one that operates in a step-forward manner. At each step in the analysis, the particular variable entered into the regression equation accounts for the greatest amount of variance between it and the dependent variable, i.e., the variable with the highest partial correlation with the dependent variable. The program is flexible to allow any independent variable to be: (1) left free to enter the regression equation by a criterion of the sum of squares reduction; (2) forced into the regression equation; or (3) kept definitely out of the regression equation in one given selection. The procedure permits examination of several alternative considerations of the independent variables. It is done by optional selections of variables to be forced in and out of the regression equation, or to be simply left free to enter the equation using variance reduction criteria.

Observation of the relative change in the standard error of estimate was used as the stopping rule in the regression analysis. An increase of the standard error at a given step indicates that the additional information realized by introducing the variable is off-set by the loss in degrees of freedom. This implies that the particular variable can be eliminated in the regression equation.

The Students T statistics computed for each of the regression coefficients of the final relationships all exceeded 4.0, and averaged about 9.5 using the aforementioned stopping rule. A value of 1.96 is considered statistically significant at 95 percent confidence limits for large sample size (greater than 100 observations).

Sewer Sediment Solids Loading Models

Introduction

Regression results reported in earlier work (Pisano and Queiroz, 1977 and 1984) are summarized in this section. Various predictive models are described, relating total suspended solids deposition within a collection system with independent variables under the assumption of clean pipe conditions. These relationships are therefore applicable for situations in which the sewer piping system is properly maintained. These equations were developed from data assembled from three major sewerage systems in Eastern Massachusetts and one in Cleveland, Ohio.

General Description

The physical characteristics of the three major collection systems used in this analysis derived from three prior studies. The first area, covering portions of West Roxbury In Boston, Dedham, Newton arid Brookline is strictly separated. The second area covering major portions of Dorchester and South Boston, two neighborhoods of the Boston metropolitan area, is a mixed, combined and separate area, while the third basin covering a portion of the City of Fitchburg is served by a combined sewer system. The total pipe footage for all three areas entails 196 mi of separate and combined sewer systems encompassing a total area of 8.9 mi^2.

The Easterly District in the City of Cleveland is bordered on the west by the Westerly District extending along the Cuyahoga River; on the south by the Southerly District, generally extending along Woodland, Holton, Parkhill and Abell Avenues; on the east by the communities of Euclid, Cleveland Heights, South Euclid, East Cleveland, and Shaker Heights; and on the north by Lake Erie. The Easterly District of the City totals approximately 16,000 acres and includes the downtown area, with an additional 25,000 acres tributary from the surrounding areas. The existing sewerage system within the Easterly District is almost entirely combined. Tributary areas outside of the city use sewers and drains for conveyance of drainage to downstream water courses. The available topographic data showed that most of the Easterly District is relatively flat with a ground slope under 2.0% averaging at about 0.5%.

Alternative Model Selections

In this section several regression models are recommended for user application. Alternative forms reflecting the availability of data and/or user resources will be presented. The simple forms require little data and have the least predictive reliability, whereas the more complicated models, requiring greater user resources and data availability, provide estimates with higher reliability.

Equations calibrated with field data collected from Boston and Fitchburg, MA and Cleveland, OH (Pisano and Queiroz, 1984) are:

Boston and Fitchburg, MA:

Simplest Model:

$[R^2 = 0.85]$: $TS = 0.0011\ (L^{1.1})(S^{-0.44})(Q^{-0.51})$ ……………………………………….(17)

Intermediate Model:

$[R^2 = 0.85]$: $TS = 0.0013\ (L^{1.2})(D^{0.61})(A^{-0.18})(S^{-0.42})(Q^{-0.51})$ ………………………………(18)

Elaborate Model:

$[R^2 = 0.95]$: $TS = 0.00073\ (L^{0.81})(S_{PD}^{-0.82})(S_{PD/4}^{-0.11})(Q^{-0.51})$ ……………………………(19)

Cleveland, OH:

Simplest Model:

$[R^2 = 0.88]$: $TS = 0.0012\ (L^{1.1})(S^{-0.43})(Q^{-0.54})$ ……………………………………..……..….(20)

Elaborate Model:

$[R^2 = 0.94]$: $TS = 0.00017\ (L^{0.95})(S^{-0.32})(S_{PD}^{-0.52})(S_{PD/4}^{-0.15})(Q^{-0.52})$ …………………….…..(21)

Where:

- A = service area of collection sewer system, acre
- D = average sewer diameter, in.
- L = total sewer length, ft
- L_{PD} = sewer length corresponding to 80% of the solids deposited in the sewer system, ft
- Q = flowrate per capita, including allowance for infiltration, gpcd
- S = average sewer slope, m/m
- S_{PD} = sewer slope corresponding to L_{PD}, ft/ft
- $S_{PD/4}$ = sewer slope corresponding to ¼ of the percentage of sewer length (L_{PD}) below which 80% of the solids deposit, ft/ft
- TS = daily total wastewater solids deposition loading in collection system, lb/d

As shown above, all R^2 values of these regression models are ≥ 0.85. The differences of R^2 values between Boston and Fitchburg, MA and Cleveland, OH are < 5% for the Simplest Model and < 1% for the Elaborate Model. However, with all of the uncertainties involved in such calculations, $R^2 = 0.94$ may be as good as $R^2 = 0.85$. With this in mind, using the Simplest Model for a load calculation could be very useful.

Effects of Age and Maintenance

The above regression equations were derived from deposition data computed under the assumption of clean pipes with no bottom sediments from prior storms. In this section the impact of poorly maintained systems was examined by arbitrarily assuming various levels of prior sediment accumulation in the pipes (Pisano and Queiron, 1977). These sediment levels would change the bottom cross-sectional shape of the pipe channel, the depth of flow, the hydraulic radius, and the shear stress characteristics accordingly.

Two cases simulating different degrees of maintenance other than perfect clean pipe conditions were considered. In the first case, or the intermediate maintenance category, sediment beds ranging from 1 to 3 in. in depth were assumed for all pipes with slopes < 0.0075. A sediment bed of 3 in. was assumed for all pipes with slopes < 0.0005. The bed depths then ranged linearly starting at 3 in. for a pipe slope of 0.0005 up to one in. for a pipe slope of 0.0075. This range was established using judgment and also based on visual inspection of numerous combined sewer laterals in eastern Massachusetts sewerage systems. In the second category of maintenance, the zero maintenance case, sediment beds ranging from 3 to 6 in. for the same range of slopes was considered.

Considering the two age and maintenance criteria mentioned here, the deposition model was used to estimate total deposition loadings for each of the 75 sewer systems for each of the four per capita waste generation rates of 40, 110, 190 and 260 gpcd. Before similar regression computations were performed on the deposition results obtained for pipes with bottom deposits, a comparison was made of the total deposited loads computed under the assumptions of clean and sedimented pipes.

For each basin the ratios of *TS* computed for sedimented pipes with sediment beds of 1 to 3 in. and 3 to 6 in. and the *TS* values for clean pipes were calculated for all four per capita waste rates considered, i.e., 40, 110, 190 and 260 gpcd. The resulting ratios were very stable for a given per capita waste rate for both cases of sediment deposits. The mean and coefficient of variation of these ratios are presented in Table 18 for both conditions of bottom deposits.

Table 18. Average values of the ratios of computed loads in deposited pipes over clean pipes

Ratios	Average Values of Ratios for per Capita Wastewater Rates (gpcd)			
	40	110	190	260
$TS_{1\text{-}3\text{ in. prior sediment}}/TS_{\text{clean pipe}}$	1.263 (0.18)	1.186 (0.14)	1.128 (0.07)	1.094 (0.12)
$TS_{3\text{-}6\text{ in. prior sediment}}/TS_{\text{clean pipe}}$	1.312 (0.14)	1.211 (0.11)	1.151 (0.09)	1.121 (0.09)

Note: The numbers in parenthesis indicate the coefficient of variation of the ratios.

The results shown on Table 18 suggest that the prediction of TS in sedimented pipes could be accomplished by a simple functional multiplicative correction of the results given by any of the regression equations for clean pipes. An equation was fitted using the data of Table18 for each of the bed deposit conditions. These equations are:

For a system with deposits ranging from 1 to 3 in.:

$$TS_{1\text{-}3\text{ in.}} = 1.68\, Q^{-0.076}\, TS_{\text{clean}} \qquad (R^2 = 0.988) \quad (22)$$

For a system with deposits ranging from 3 to 6 in.:

$$TS_{3\text{-}6\text{ in.}} = 1.79\, Q^{-0.084}\, TS_{\text{clean}} \qquad (R^2 = 0.999) \quad (23)$$

Where: Q = flow per capita, and TS_{clean} = load of total solids computed from any of the above regression equations (Eq. 17 to 21).

The R^2 values indicated above refer to the regression of the ratios of *TS* on the values of flow per capita. The small difference found between the two conditions of bottom deposits may well be the result of an inappropriate accounting of these factors by the deposition model. On the other hand it may simply have resulted from the particular combination of pipe diameters and sediment depths used as data, which may have led to actually small differences in flow depths above the sediment levels, and therefore small differences in shear stress between the cases.

Organic Pollutant Loading

A regression was performed between *TS* and each one of the other 6 indicators, including BOD_5, *COD, TKN*, NH_3, *P*, and *VSS* (Pisano and Queiron, 1977). The resulting regression equations are presented in Table 19, with their associated correlation coefficients. Estimates of the total daily BOD_5, *COD, TKN*, NH_3, *P* and *VSS* depositing loads within a given collection system can be made using the regression equations in Table 19 with the predicted *TS* loading calculated from any of the regression equations (Eq. 17 to 22) for clean pipe conditions and the bias correction factors for pipes with sediment beds given in Eq. 23.

Table 19. Regression of different pollutants on *TS*

Regression Equation (lb/d)	Correlation Coefficient
$BOD_5 = 0.344\, TS^{1.308}$	0.80
$COD = 0.875\, TS^{1.04}$	0.77
$TKN = 0.039\, TS^{1.135}$	0.67
$NH_3 = 0.017\, TS - 0.0336$	0.44
$P = 0.0076\, TS - 0.006$	0.67
$VSS = 0.689\, TS^{1.308}$	0.97

Estimate of Sewer Length and Slope

The total sewer length of the combined sewer system, L, is generally assumed to be known. In cases where it is not known, crude estimates may suffice and the estimated sewer length, L', can be determined from the service area of the collection sewer system, A, using the following expressions (Pisano and Queiron, 1977):

For low population density (10 – 20 people/acre)

$$L' = 169\,(A)^{0.93}; \quad (R^2 = 0.82) \qquad (24)$$

For moderate-high population density (30 – 60 people/acre)

$$L' = 239\,(A)^{0.93}; \quad (R^2 = 0.82) \qquad (25)$$

If data on pipe slope is not available, the average sewer slope, S', can be estimated from the average ground slope S_g using the following equation (Pisano and Queiron, 1977):

$$S' = 0.35(S_g)^{0.82}; \quad (R^2 = 0.96) \qquad (26)$$

Procedure for Estimating *TS* Deposited

As indicated in Eqs. 17 through 21, the R^2 values between Simplest Models and Elaborate Models are 0.85 and 0.95 for Boston and Fitchburg, MA and 0.88 and 0.94 for Cleveland, OH, respectively. They are < 5% for the Simplest Model and < 1% for the Elaborate Model. With all of the uncertainties involved in such calculations, R^2 = 0.94 may be as good as R^2 = 0.85. With this in mind, using the Simplest Model for a load calculation is illustrated in the following generalized procedure for estimating *TS* deposited as shown in Figure 2.

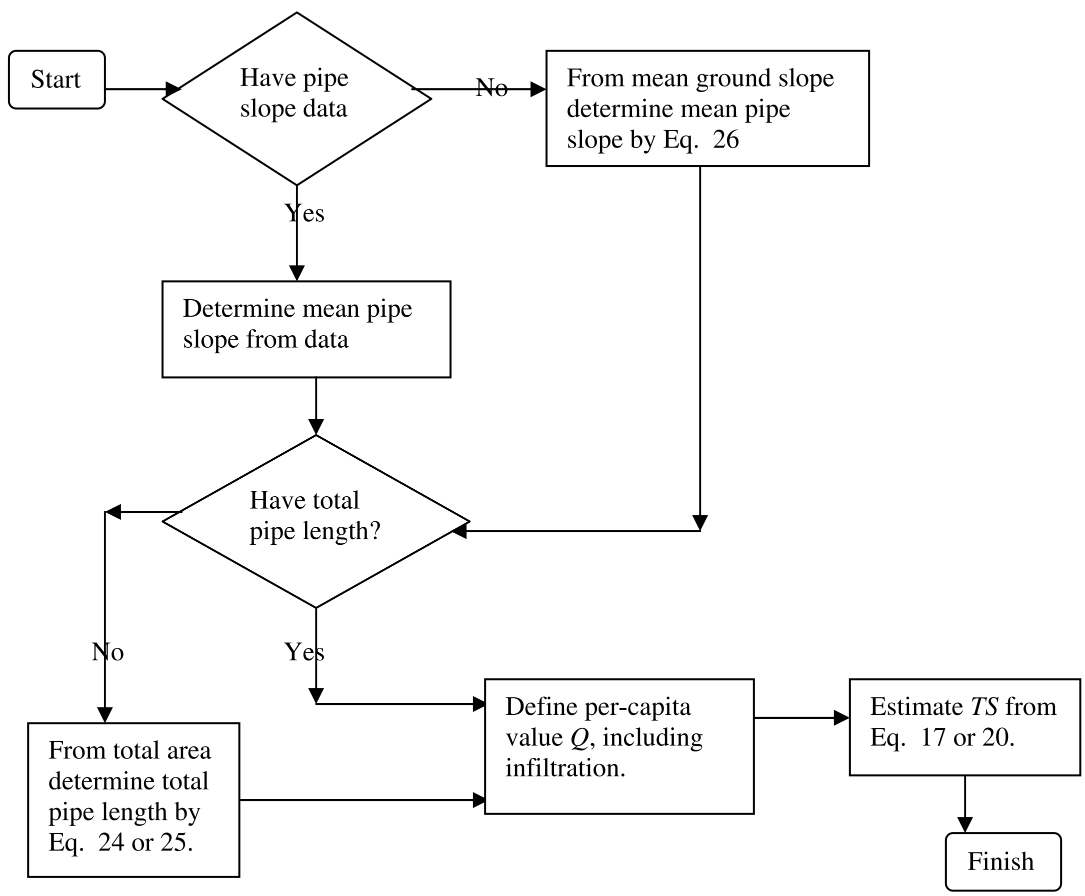

Figure 2. Steps to Determine Deposited Solids (*TS*).

Hypothetical-Case Example

A hypothetical urban watershed is presented to illustrate the application of pollutant loading estimation methods as described in this chapter. The total drainage area in this example is approximately 1,200 ha which consists of a mixture of land uses as described in Table 7 (Chapter 3). The sewer length of each land use category is estimated and summarized in Table 20.

Table 20. Sewered area in each category of land-use

Land Use	Area (ha)
Low density residential areas	300
High density residential areas	100
School	20
Commercial areas	200
Light industrial areas	100

The Simplest Model (Eq. 17) was used for calculating sewer sediment solid loading. Results are summarized in Table 21.

Table 21. Estimated sewer sediment solids loading

Land-use	Population Density (p/ha)	Sewer Length(1) (m)	Sewer Slope(2) (m/m)	Solids Loading(3) (kg/d)
Low density residential	30	24,000	0.01	36.3
High density residential	150	12,000	0.01	17.0
Commercial areas	150	23,000	0.01	34.7
Light industrial areas	150	12,000	0.01	17.0
Total				105.0

(1) Estimates were based on population density and Equations 24 and 25
(2) Estimates were based on ground slope and Equation 26
(3) Estimates were based on Equation 17; flowrate per capita, Q = 200 L/d

The estimated total annual sewer-sediment solids loading is 38,300 kg.

By using the equations listed in Table 19, the organic pollutants associated with *TS* can be estimated. Results are summarized in Table 22.

Table 22. Estimated organic pollutant loading

Regression Equation (lb/d)	Organic Pollutant Loading		
	lb/d	kg/d	kg/yr
$BOD_5 = 0.344\ TS^{1.308}$	152.0	70.0	25,550
$COD = 0.875\ TS^{1.04}$	111.0	50.0	18,250
$TKN = 0.039\ TS^{1.135}$	7.7	3.5	1,280
$NH_3 = 0.017\ TS - 0.0336$	1.8	0.8	300
$P = 0.0076\ TS - 0.006$	0.8	0.4	150
$VSS = 0.689\ TS^{1.308}$	303.0	137.0	50,000

Table 22 results show that the sediment solids contain high level of decomposed human wastes that are the main source of sulfide ($S^{=}$) (Nielsen 1991). The root cause of odor and corrosion in collection systems is $S^{=}$, which is produced from sulfate by bacteria residing in a slime layer on the submerged portion of sewer pipes and structures. Identification of potential problem areas before structure damage requires field investigation of $S^{=}$ concentrations in the sewerage system being addressed in Chapter 5.